MSRs for the Future

Workshop on Molten Salt Reactor Technologies—
Commemorating the 50th Anniversary of the Startup of the MSRE

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Overview

• Context
  - Need for innovation in future nuclear reactor technology
  - Successful innovation in other industries
  - Changing U.S. environment for innovation

• Molten salts: why are they different?

• Molten salts: where are we now?

• Molten salts: what are the next steps?
Today’s fission reactors are remarkably expensive to build!!

<table>
<thead>
<tr>
<th>Commodity Input</th>
<th>Commodity Price (1) ($/kg)</th>
<th>1000-MW Gen II Pressurized Water Reactor (2) kg/kW</th>
<th>$/kWpeak</th>
<th>2-MW Vestas V90 wind turbine in 50-MW field (3) kg/kW</th>
<th>$/kWpeak</th>
<th>0.15-MW (196-Hp) Chevy Malibu automobile (4) kg/kW</th>
<th>$/kWpeak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>$0.03</td>
<td>180.06</td>
<td>$5.85</td>
<td>375.44</td>
<td>$12.20</td>
<td>7.547</td>
<td>$4.83</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>$0.64</td>
<td>33.99</td>
<td>$21.75</td>
<td>110.56</td>
<td>$70.76</td>
<td>0.197</td>
<td>$1.01</td>
</tr>
<tr>
<td>Copper/brass</td>
<td>$5.13</td>
<td>0.73</td>
<td>$3.74</td>
<td>3.32</td>
<td>$17.02</td>
<td>0.715</td>
<td>$1.14</td>
</tr>
<tr>
<td>Aluminum</td>
<td>$1.60</td>
<td>0.02</td>
<td>$0.03</td>
<td>3.20</td>
<td>$5.12</td>
<td>0.715</td>
<td>$1.14</td>
</tr>
<tr>
<td>Inconel</td>
<td>$10.50</td>
<td>0.12</td>
<td>$1.30</td>
<td></td>
<td></td>
<td>0.249</td>
<td>$0.41</td>
</tr>
<tr>
<td>High-alloy steel</td>
<td>$1.79</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.021</td>
<td>$0.10</td>
</tr>
<tr>
<td>Nickel</td>
<td>$10.50</td>
<td>0.00</td>
<td>$0.01</td>
<td></td>
<td></td>
<td>0.000</td>
<td>$1.65</td>
</tr>
<tr>
<td>Lead</td>
<td>$1.74</td>
<td>0.05</td>
<td>$0.08</td>
<td></td>
<td></td>
<td>0.161</td>
<td>$1.76</td>
</tr>
<tr>
<td>Magnesium</td>
<td>$4.59</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.049</td>
<td>$0.41</td>
</tr>
<tr>
<td>Platinum</td>
<td>$31,800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.304</td>
<td>$0.60</td>
</tr>
<tr>
<td>Plastic/paint</td>
<td>$1.52</td>
<td>0.05</td>
<td>$0.08</td>
<td>26.78</td>
<td>$40.65</td>
<td>1.161</td>
<td>$1.76</td>
</tr>
<tr>
<td>Rubber</td>
<td>$1.63</td>
<td></td>
<td></td>
<td>0.249</td>
<td>$0.41</td>
<td>0.249</td>
<td>$0.41</td>
</tr>
<tr>
<td>Glass/ceramic</td>
<td>$2.00</td>
<td>0.92</td>
<td>$0.92</td>
<td>9.56</td>
<td>$19.12</td>
<td>0.301</td>
<td>$0.60</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>$1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.20</td>
<td>$6.15</td>
</tr>
<tr>
<td>Electronics</td>
<td>$5.13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.19</td>
<td>$11.50</td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td>216</td>
<td>$33.76</td>
<td>542</td>
<td>$192.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase price ($/peak kW) (5)</td>
<td>$5,000</td>
<td>$1,750</td>
<td>$154</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commodity % of peak kW price</td>
<td>0.68%</td>
<td>11.0%</td>
<td>7.46%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ratio nuclear com. % of price vs. otl</td>
<td>1.0</td>
<td>16.3</td>
<td>11.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nuclear commodity cost is $37.51/kW_{ave}, vs. wind $539/kW_{ave}
Third Way study identified 7 current molten salt development efforts

“Third Way has found that there are more than 40 companies, backed by more than $1.3 billion in private capital, developing plans for new nuclear plants in the U.S. and Canada.”

http://www.thirdway.org/infographic/nuclears-continuing-evolution
New technologies for space launch provide interesting analogies for advanced nuclear

- Designed for reusability
- Two major accidents (astronauts perished)
- Liquid hydrogen/oxygen and solid rocket boosters
- Lifetime launch cost: $60,000/kg

- Designed for reliability and low cost (reusability available soon)
- One major accident June 2015 (Dragon capsule survived)
- Kerosene/liquid oxygen (LNG longer-term option)
- Current launch cost: $4,600/kg
Molten salts: why are they different?
FHRs and MSRs combine three key technologies that enable delivery of heat at high temperature.

MSR-graphite moderator structures

Liquid fluoride salt coolants

Nickel-based structural materials
Molten salts have substantial different properties than other reactor coolants

<table>
<thead>
<tr>
<th>Material Properties at 700°C</th>
<th>T_{melt} (°C)</th>
<th>T_{boil} (°C)</th>
<th>ρ (kg/m³)</th>
<th>C_p (kJ/kg°C)</th>
<th>ρC_p (kJ/m³°C)</th>
<th>k W/m°C</th>
<th>ν x 10^6 m²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7\text{Li}_2\text{BeF}_4$ (Flibe)</td>
<td>459</td>
<td>1,430</td>
<td>1,940</td>
<td>2.34</td>
<td>4,540</td>
<td>1.0</td>
<td>2.9</td>
</tr>
<tr>
<td>Sodium</td>
<td>97.8</td>
<td>883</td>
<td>790</td>
<td>1.27</td>
<td>1,000</td>
<td>62</td>
<td>0.25</td>
</tr>
<tr>
<td>Lead</td>
<td>328</td>
<td>1,750</td>
<td>10,540</td>
<td>0.16</td>
<td>1,700</td>
<td>16</td>
<td>0.13</td>
</tr>
<tr>
<td>Helium (7.5 MPa)</td>
<td>3.8</td>
<td>5.2</td>
<td>20</td>
<td>0.29</td>
<td>11.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water (7.5 MPa) †</td>
<td>0</td>
<td>100</td>
<td>732</td>
<td>5.5</td>
<td>4,040</td>
<td>0.56</td>
<td>0.13</td>
</tr>
</tbody>
</table>

† Water properties at 290°C for comparison

- **High volumetric heat capacity**
  - Results in compact reactor primary system, low circulating power
- **High boiling temperature**
  - Intrinsically low pressure, thin-walled primary coolant boundary
- **Chemically stable coolant compatible with graphite**
  - Core internal structures have very large thermal margins
U.S. university and laboratory R&D has focused on understanding FHRs

**Multiple FHR Conceptual Design Studies**

- 2008 900 MWt PB-AHTR
- 2010 125 MWt SmAHTR
- 2012 3600 MWt ORNL AHTR
- 2014 236 MWt Mk1 PB-FHR

**Experiments and Simulation**

- UW/MIT flibe corrosion/irradiation
- NGNP AGR

**Expert Workshops and White Papers**


MSRs for the Future
Multiple start-up companies are now developing liquid-fueled MSRs

Thorcon

Terrestrial Energy

Flibe Energy

Transatomic

Europeans are also studying fast-spectrum MSRs
The Chinese Academy of Sciences is pursuing development of both solid and liquid fueled molten salt reactors.
Molten salts: what are the next steps?
FHRs and MSRs have remarkably compact reactor vessels compared to HTGRs and SFRs

<table>
<thead>
<tr>
<th>Reactor Vessel</th>
<th>Type</th>
<th>Power (MWe)</th>
<th>Diameter (m)</th>
<th>Height (m)</th>
<th>Specific power (MWe/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mk1 PB-FHR</td>
<td>FHR</td>
<td>100</td>
<td>3.5</td>
<td>12.0</td>
<td>0.87</td>
</tr>
<tr>
<td>2012 ORNL AHTR</td>
<td>FHR</td>
<td>1530</td>
<td>10.5</td>
<td>19.1</td>
<td>0.93</td>
</tr>
<tr>
<td>Thorcon</td>
<td>MSR</td>
<td>250</td>
<td>5.0</td>
<td>5.7</td>
<td>2.26</td>
</tr>
<tr>
<td>1966 Molten Salt Breeder Reactor</td>
<td>MSR</td>
<td>1000</td>
<td>5.0</td>
<td>5.8</td>
<td>8.93</td>
</tr>
<tr>
<td>Westinghouse 4-loop</td>
<td>PWR</td>
<td>1092</td>
<td>6.0</td>
<td>13.6</td>
<td>2.84</td>
</tr>
<tr>
<td>PBMR</td>
<td>HTGR</td>
<td>175</td>
<td>6.2</td>
<td>24.0</td>
<td>0.24</td>
</tr>
<tr>
<td>S-PRISM</td>
<td>SFR</td>
<td>380</td>
<td>9.2</td>
<td>19.6</td>
<td>0.29</td>
</tr>
</tbody>
</table>

- Compact size and low mass of FHR and MSR reactor vessels makes periodic replacement practical and economic.
- Replacibility enables a “limited warrantee” on components that must operate at high temperature.
LWR thermal hydraulics codes work well for FHRs, but FHRs have key differences

- LWR thermal hydraulics codes appear to work well for FHRs
- FHRs have large thermal margin to fuel damage during design-basis accidents
  - LWR operating limits established by fuel-damage limits
  - FHR operating limits established by primary coolant boundary limits
- FHRs operate with low coolant volumetric flow rates
  - Low pumping power
  - Flow regimes commonly in transition or laminar regime
  - Single-phase flow unless gas entrainment occurs

Expert workshops in 2012 developed recommendations for thermal hydraulics methods and validation for FHRs
The similitude of convective heat transfer in oil and molten salts was discovered in 2005

- By appropriate scaling, it is possible to simultaneously match Reynolds, Froude, Prandtl, and Grashof numbers.

- Mechanical pumping power and heat input reduced to 1 to 2% of prototype power inputs.

- Steady state and transient heat transfer to steel and graphite structures can also be reproduced.

New experiments to verify similitude for key FHR/MSR phenomena will be valuable.
It is much easier to study convective heat transfer with oils than with molten salts

• Oils have been used over many years to study convective heat transfer phenomena
  - Many different instrumentation options are available

• Key questions involve understanding scaling distortions
  - Thermal radiation, surface tension, etc.?

Benjamin Gebhart, 1973, Interferogram for natural convection in silicone oil from a heated plate (two sides)

Bardet et al., 2005, particle image velocimetry in Drakesol swirling flow

Scaled Dowtherm Integral Effects Test facilities have low cost

UCB Compact Integral Effects Test (CIET) In Operation

CIET Front View

Nodalization for CIET/FHR simulation
Materials and component testing should accelerate further

- Capabilities to manufacture and purify fluoride salts has been reestablished in U.S., China and Czech Republic
- Static corrosion tests have found favorable performance for structural materials (316, Alloy N, graphite) with clean flibe
- A variety of loop tests have been constructed and are planned in China and the U.S.
- In-reactor irradiation in the MITR is providing valuable information on materials performance and tritium generation/transport/recovery
- Multiple options exist for salt chemistry control
- Modern electrochemical diagnostics are being applied to measure salt chemistry
Conclusions on Next Steps
Conclusions on Next Steps

- Initial focus of commercial development for FHRs and MSRs will be on smaller reactors (50-600 MWe/module)
  - Expect designs that allow replacement of high-temperature components (including reactor vessels)
- FHRs and MSRs will remain a major focus of start-up efforts
  - Analogies with NASA Commercial Orbital Transfer Services program
  - Lower entry barriers due to:
    » High thermal margin to core structural damage compared to SFRs and LFRs
    » Ability to use passive LWR safety codes and inexpensive separate and integral effect test data
    » MSRs - low fuel development costs balanced by complex accident source terms and licensing
    » FHRs - higher fuel development cost balanced by simplified design and licensing
  - Chinese TMSR program, along with U.S. university and lab R&D, will significantly influence development rates and strategies
Questions?
Notional 12-unit Mk1 PB-FHR nuclear station
1200 MWe base load; 2900 MWe peak

1) Mk1 reactor unit (typ. 12)
2) Steam turbine bldg (typ. 3)
3) Switchyard
4) Natural gas master isolation
5) Module assembly area
6) Concrete batch plant
7) Cooling towers (typ. 3)
8) Dry cask storage
9) Rad. waste bldg
10) Control room bldg
11) Fuel handling bldg
12) Backup generation bldg
13) Hot/cold machine shops
14) Protected area entrance
15) Main admin bldg
16) Warehouse
17) Training
18) Outage support bldg
19) Vehicle inspection station
20) Visitor parking

For more info: http://fhr.nuc.berkeley.edu